

Chapter 6:

Tables and Figures

List of Tables

Table 6-1. Estimate of metals mass in three segments of the upper Animas River.	25
Table 6-2. Average annual metals dissolved and particulate load of the Animas River at Durango.....	32
Table 6-3. Comparison of Gold King plume transport at Durango compared to the mass carried during the peak days of snowmelt runoff.	33

List of Figures

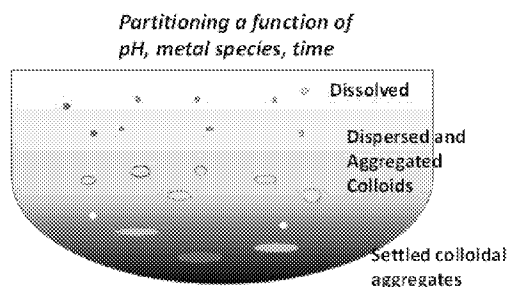
Figure 6-1. Method for calculating load. Illustration of metals load calculation during the Gold King plume.....	5
Figure 6-2. Characteristics of particles carried in the plume.....	6
Figure 6-3. The metals mass transported past each location estimated by the modeling methods..	7
Figure 6-4. Colloidal/particulate estimated by the empirical model at Animas River locations..	8
Figure 6-5. Mass of individual metals in Animas. Mass of arsenic (A), lead (B), copper (C), and zinc (D) transported in the Gold King plume in the Animas River.	9
Figure 6-6. Mass of metals transported during the Gold King plume at the junction of the Animas and the San Juan Rivers based on the empirically modelled plume.....	10
Figure 6-7. Total mass estimated by the WASP water quality model and the empirical model..	11
Figure 6-8. Characteristics of deposited materials..	12
Figure 6-9. WASP and the empirical model estimate the mass of metals at modeled locations using different methods..	13
Figure 6-10. Deposition of Gold King metals reflected valley scale geomorphic characteristics that determine river dynamics.....	14
Figure 6-11. Aerial photography of 2 Animas River segments between Silverton (A72 at RK 16.4) and Bakers Bridge (RK 64) before and after the Gold King release..	15
Figure 6-12. Aerial photograph of the braided reach of the Animas River below Baker's Bridge area at river kilometer 64. (A) June 2014 (B) August 2015 immediately post Gold King passage, and (C) October 2015 where deposition would have been high upon exiting the canyon.....	17
Figure 6-13. Deposition in the meandering channel north of Durango..	18
Figure 6-14. Channel margin deposits.	19
Figure 6-15. Masses of minerals precipitated from the release waters and Cement Creek water flowing with release waters) as these waters intermingled and reacted with Animas River water as estimated from thermodynamic modeling of titration of "Plume + Background Mean" water with calcite alkalinity that is present in the Animas.....	20
Figure 6-16. Statistical summary of summed metals mass per unit block of sediment 1 square meter x 5 cm depth collected during the and the months following the Gold King release...	21
Figure 6-17. Simulated Peak Total Sediment Concentrations Along River	22
Figure 6-18. Bed sediment concentrations in the Animas and San Juan Rivers.	23
Figure 6-19. Simulated concentrations (orange line) of total particulate metals versus river distance plotted on a log-scale.....	24
Figure 6-20.. Metals mass in streambed sediments at three locations in the upper Animas expressed as mass per unit area of streambed, based on channel dimensions and sediment characteristics.....	26

Figure 6-21. Concentration of four metals in the streambed of the San Juan River from its junction with the Animas at Farmington to Lake Powell.	27
Figure 6-22 Photographs at of the San Juan River at Ship Rock (left) and as the river heads into Lake Powell west of Mexican Hat, UT (right).	28
Figure 6-23. Comparison of metals concentrations in the streambed of the San Juan River at Mexican Hat about 50 km from Lake Powell and metal concentration in the top layers of lake core samples reported in 2014.....	28
Figure 6-24. Background concentration of dissolved metals in relation to flow.	29
Figure 6-25. Background concentration of particulate with streamflow..	30
Figure 6-26. Simulated average daily concentration and load for zinc at Durango..	31
Figure 6-27. GKM WASP estimated summed total concentrations during spring snowmelt.....	34
Figure 6-28. GKM WASP estimated concentrations during spring snowmelt..	35
Figure 6-29. Empirical simulation of average daily metal load based on regressions using only historic data and average daily flow(background) and the updated regression with 2016 data and average daily flow (2016).	36
Figure 6-30. Gold King load relative to excess in 2016.	37

Figure 6-1. Method for calculating load. Illustration of metals load calculation during the Gold King plume. Concentration during the time interval is multiplied by the flow volume during the interval. Mass per time intervals are summed. The WASP plume is terminated when 99% of the plume mass is accounted for. The empirical model was terminated subjectively when slope fades, and background was approached. The empirical model probably terminates before all metals had passed and is a minimum. WASP extends longer on the leading and trailing edges and is probably the maximum.

Materials sourced from:

- Contaminated soils outside GKM mine and the hillslope between -GKM and Cement Creek
- Scoured from Cement Creek and its floodplain
- Aggregated colloidal matter created from dissolved metals in the mine effluent itself

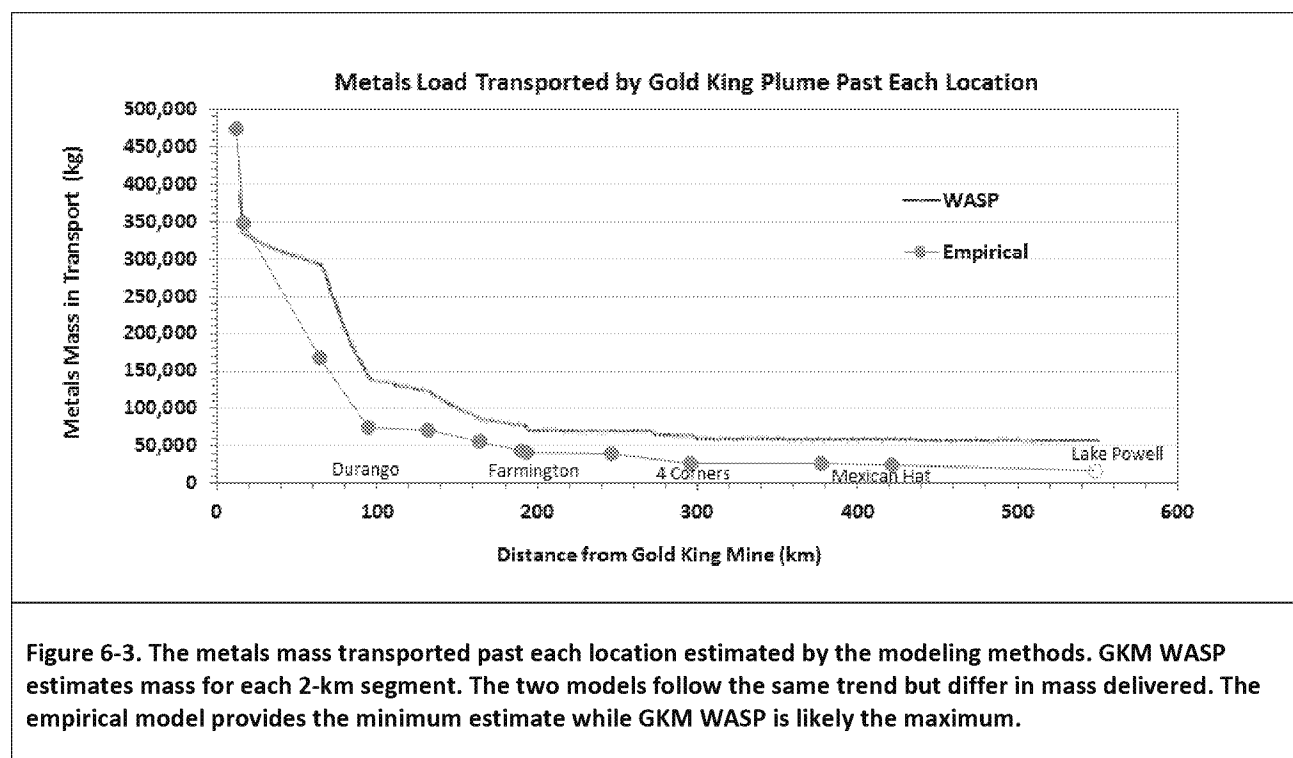
**Sediment in transport a mixture:**

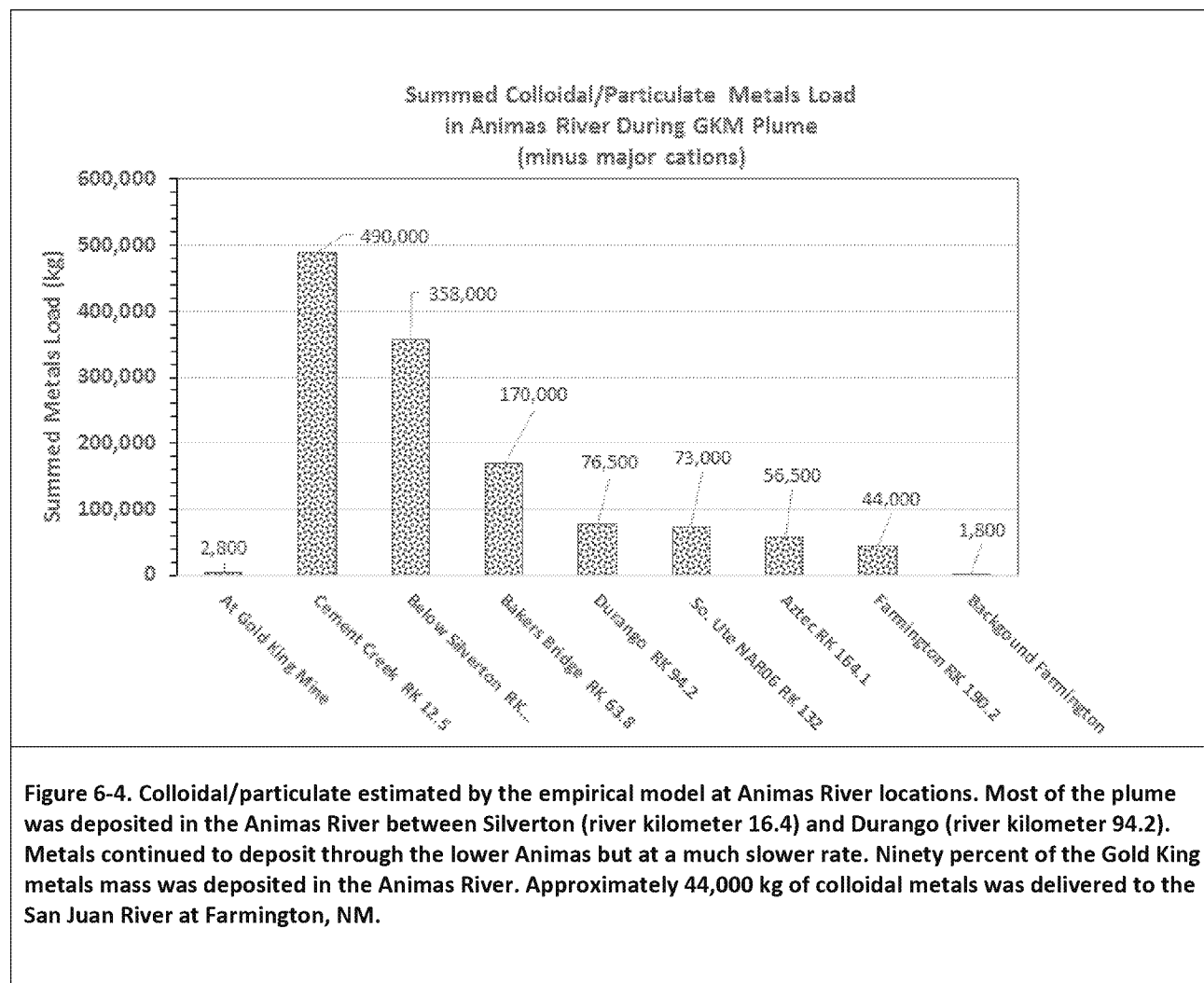
- Larger particulates (sand/silt)
- Fine particulates (clay)
- Aggregated colloidal material of varying size, texture, and stability
- Sludge-like

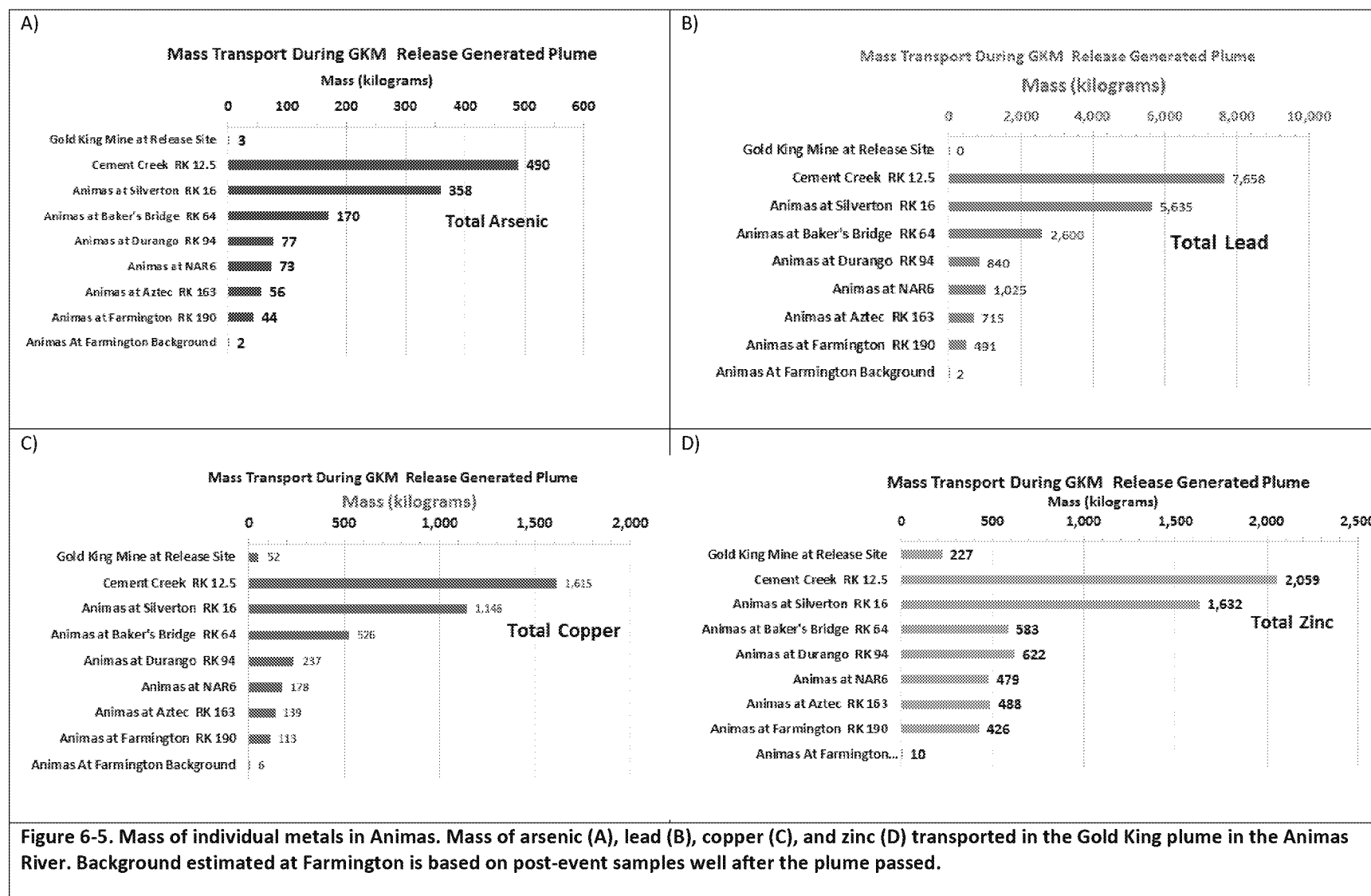
In the streambed

- Metals bound to surfaces of rocks, sand grains, clay
- Entrapped by microbes
- Mineralize eventually

Figure 6-2. Characteristics of particles carried in the plume. Metals were carried in a variety of forms in the Gold King plume. The plume entrained contaminated mine waste and sediments on the hill slope between the Gold King Mine and Cement Creek. The initial plume in Cement Creek probably carried particulates including clays, silts and sands, and possibly large particles in the North Fork Cement Creek. As the plume moved, dissolved fractions precipitated to suspended and aggregated colloids. These materials would have varying suspension and depositional characteristics as the Gold King plume flowed.







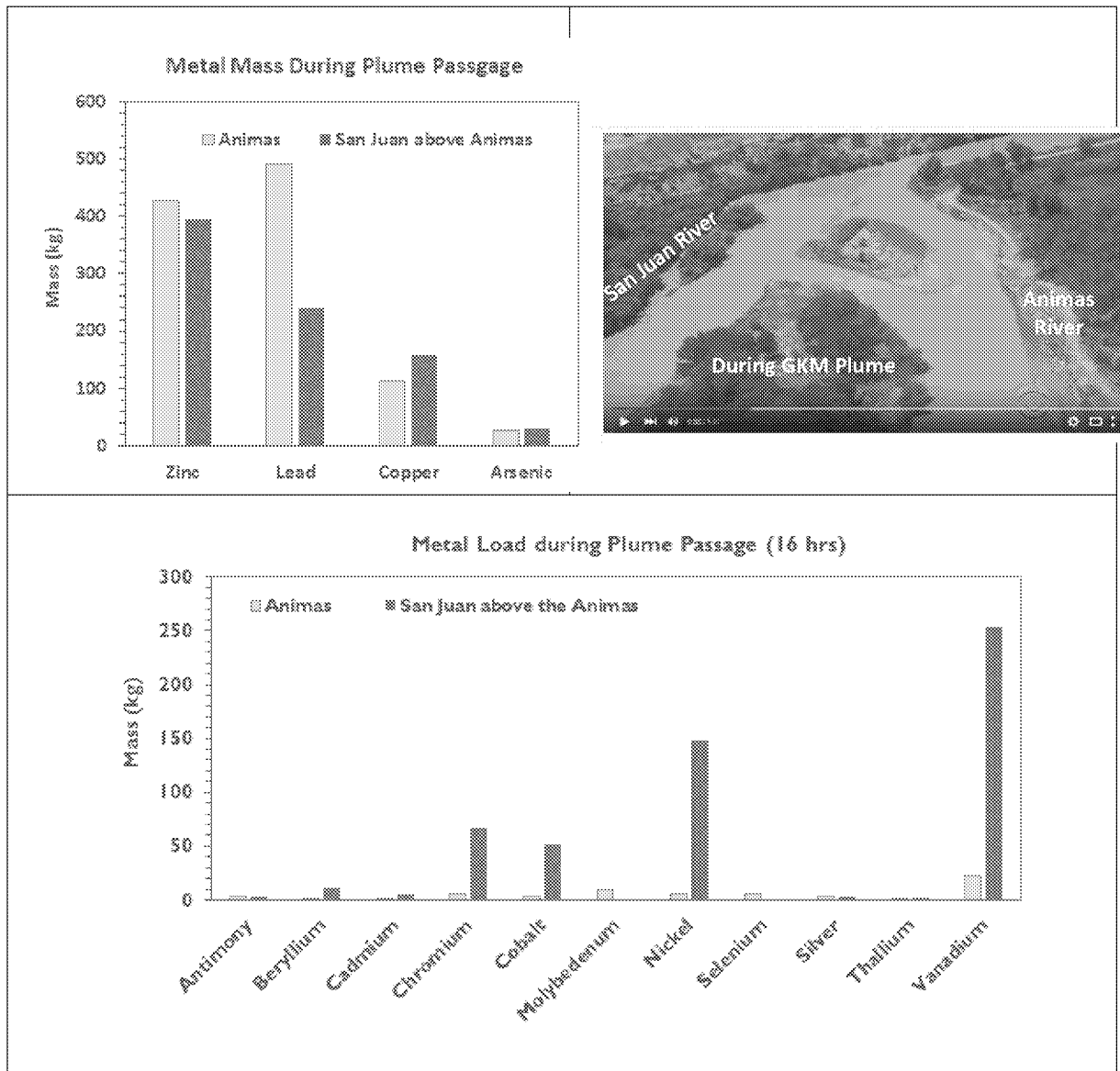


Figure 6-6. Metals mass at the confluence of the Animas and San Juan Rivers. Mass of metals transported during the Gold King plume at the junction of the Animas and the San Juan Rivers based on the empirically modelled plume. The Animas is subtracted from the San Juan site to estimate the metal concentration and mass. The two rivers were at similar flow as the plume flowed from the Animas to the San Juan. In this case, if metals were evenly contributed by the two rivers, their concentrations and loads would be equal. Most metals were higher in the San Juan, indicating sources of metals. Major exception was lead that had source as much lead as the San Juan. Several metals were comparable including zinc, copper, and arsenic. These were all elevated in the Gold King plume. Although other metals were also elevated, they would not be detectable within the background metals in the San Juan.

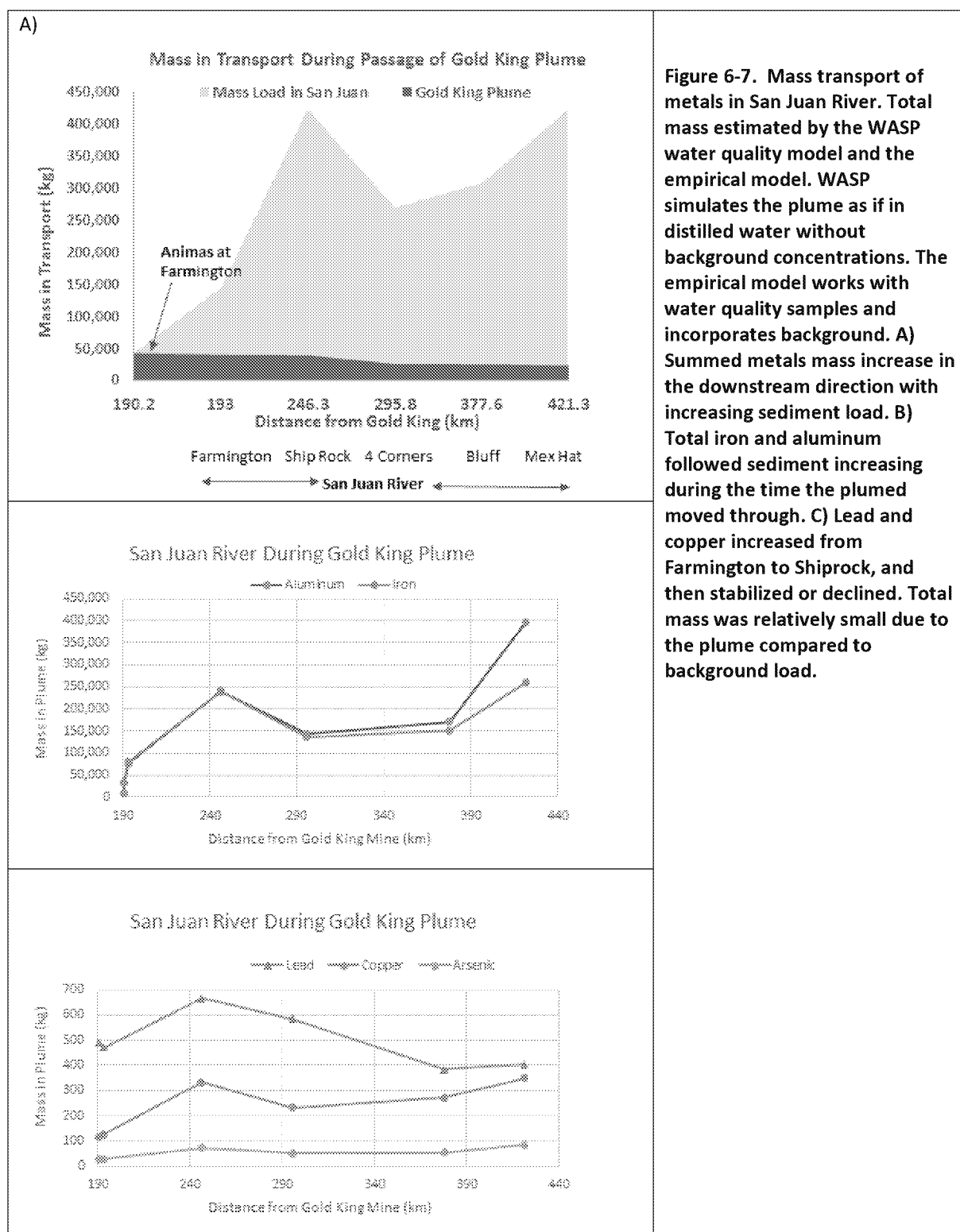


Figure 6-7. Mass transport of metals in San Juan River. Total mass estimated by the WASP water quality model and the empirical model. WASP simulates the plume as if in distilled water without background concentrations. The empirical model works with water quality samples and incorporates background. A) Summed metals mass increase in the downstream direction with increasing sediment load. B) Total iron and aluminum followed sediment increasing during the time the plume moved through. C) Lead and copper increased from Farmington to Shiprock, and then stabilized or declined. Total mass was relatively small due to the plume compared to background load.

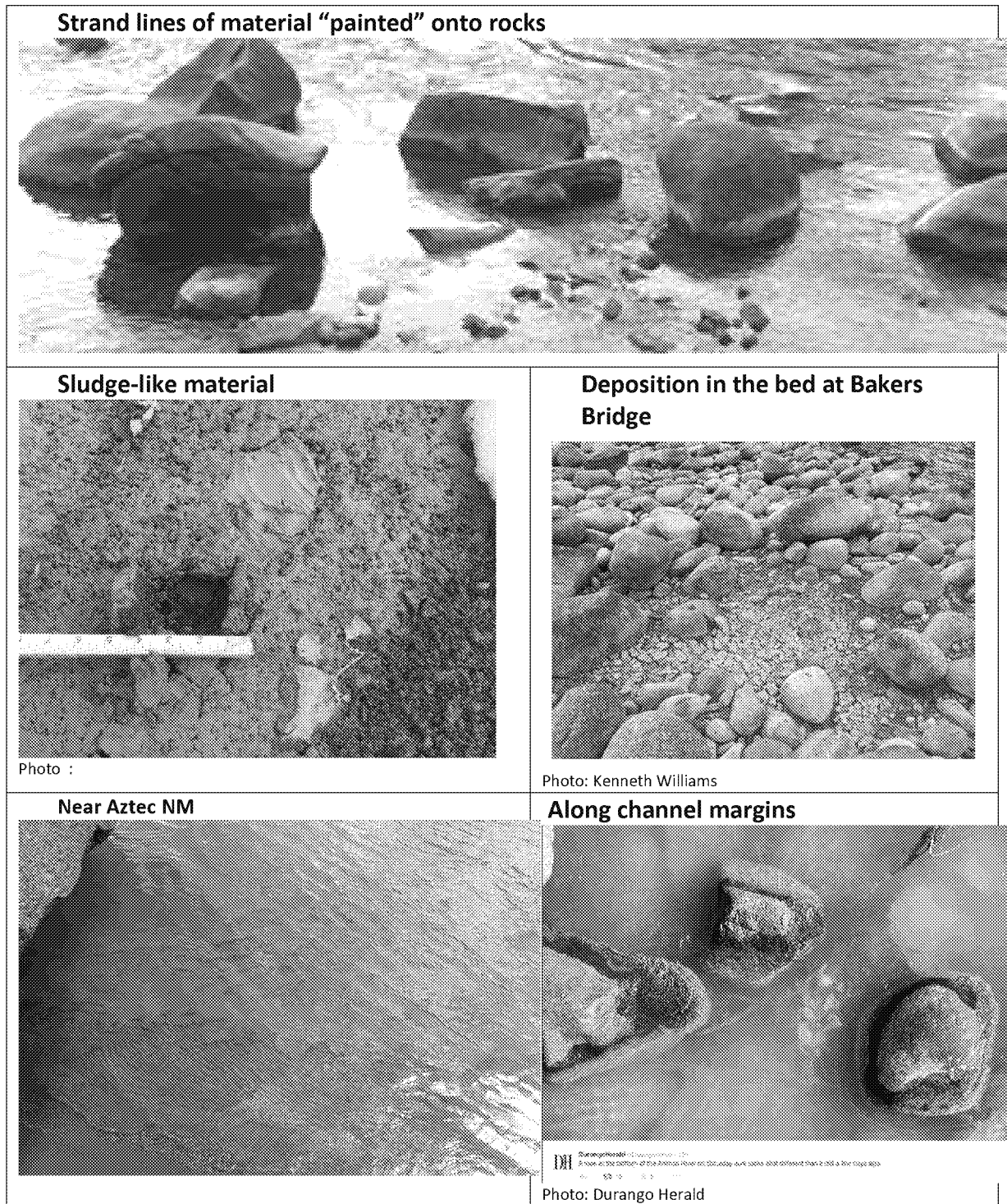
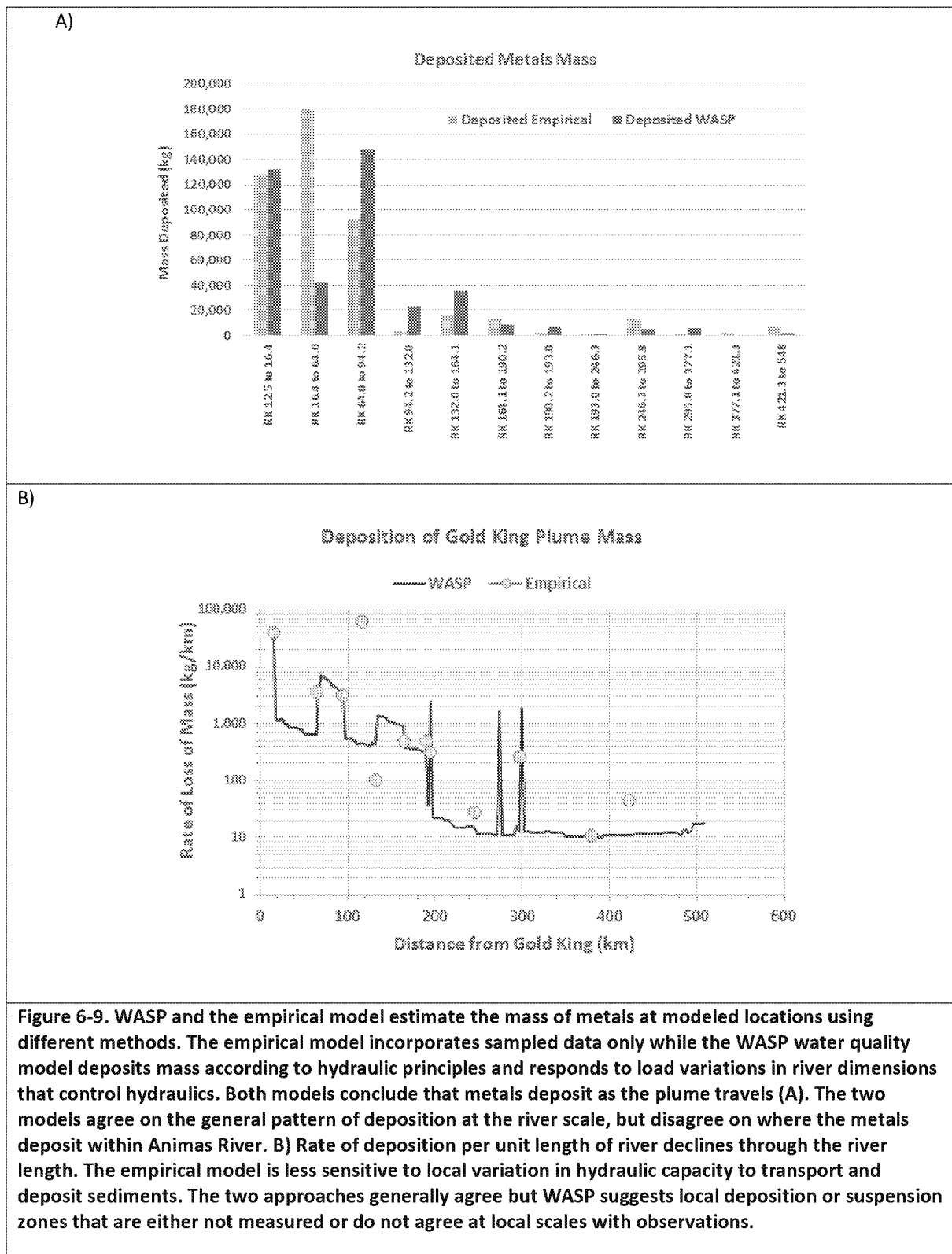


Figure 6-8. Characteristics of deposited materials. Colloidal/particulates metals existed in the water column and deposited in a variety of forms. Colloids with very small particles suspended in the water would easily travel in suspension but could “paint” rocks as strand lines. Colloids aggregated and deposited as sludge like deposits. Material settled in the channel as flow receded, settling particles and colloids with it. Aggregated colloids settled in slow velocity channel margins. D) Amorphous mass in drained slow zone.



Upper Animas valley between Cement/Animas confluence and start of canyon below Silverton (27%) (~4 km)



Photo: GoogleEarth Oct 15 2015

In the canyon reach between Silverton and Baker's Bridge (38%) (~44 km)



Photo: Mor, CC BY-NC 2.0

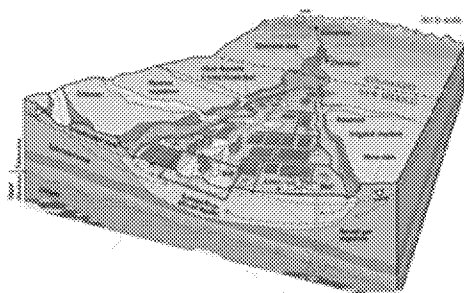


Figure 6-10. Deposition of Gold King metals reflected valley scale geomorphic characteristics that determine river dynamics. Deposition largely occurred in the headwater Animas between Silverton and Durango as the river descends from the mountainous, confined topography in the Precambrian lithology to the widened valleys associated with sedimentary rocks. Depositional zones collect deposits at several locations along the Animas where narrowly confined reaches enter widened valleys allowing deposition in the lower Animas.

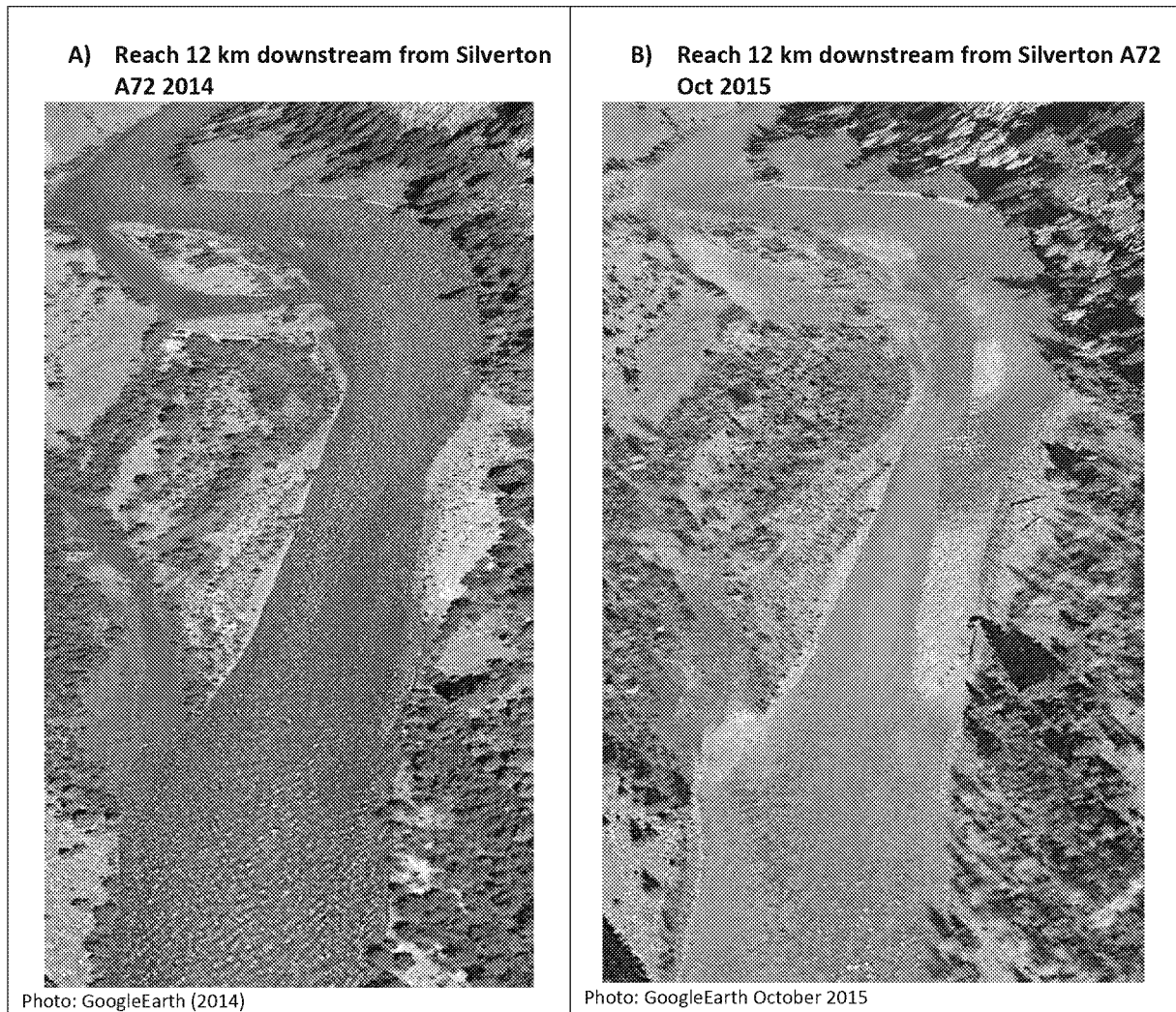


Figure 6-11. Aerial photography of 2 Animas River segments between Silverton (A72 at RK 16.4) and Bakers Bridge (RK 64) before and after the Gold King release. (A) and (B) show a reach 12 km downstream from Silverton (RK 28). Photographs (C) and (D) show a reach further into the canyon 32 km downstream from Silverton at RK 48 (next panel). Typical areas of deposition for natural sediments are channel margins and side channels that show as dark fine gravel deposits in 2014. These same areas have “yellowish” deposits in the photography three months after the Gold King plume.

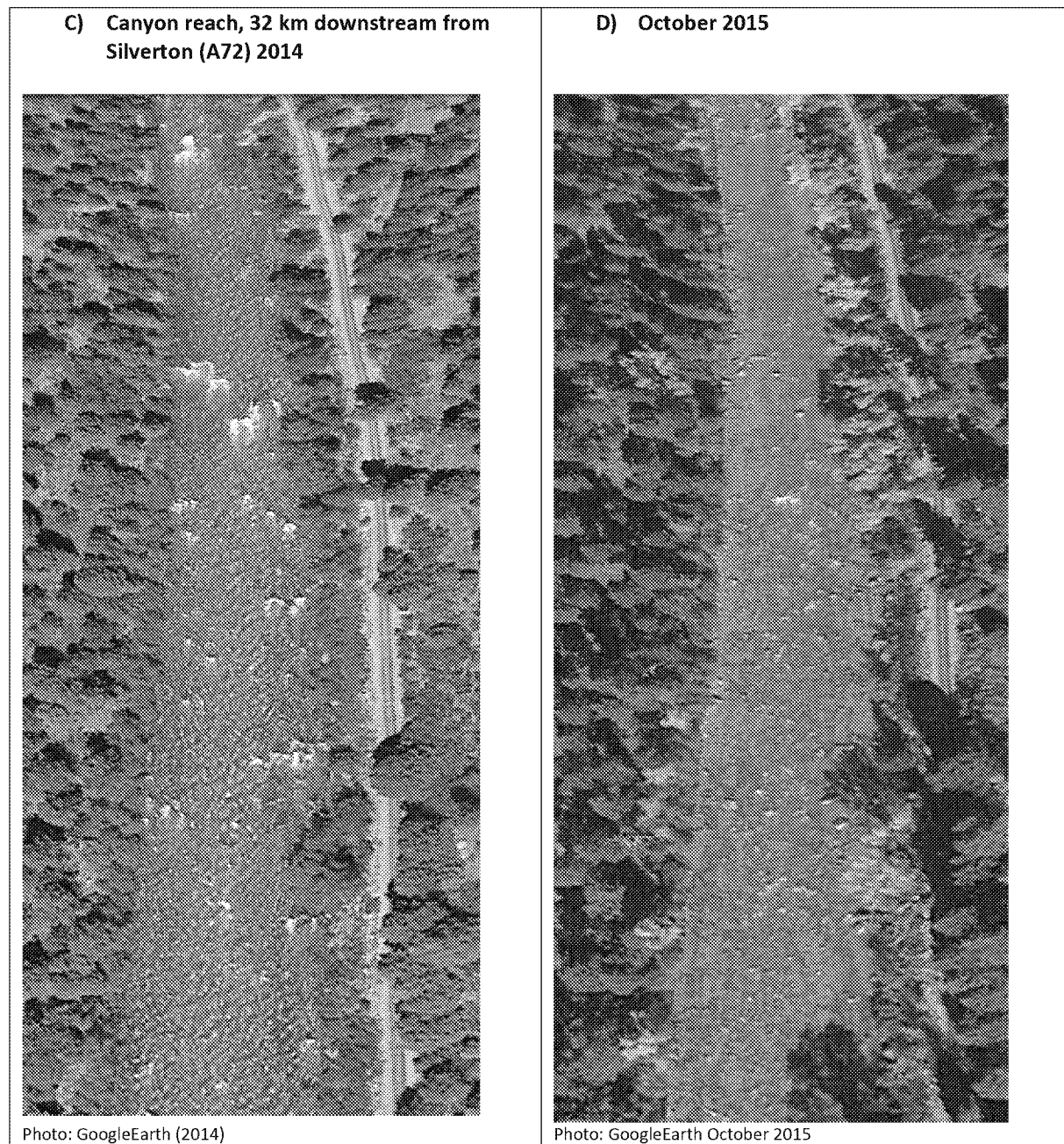


Figure 6-11 Continued. Aerial photograph of a reach of the Animas River 32 km down river from A72 below Silverton before and after Gold King Plume. C) 2014 photography at somewhat higher flow. D) October 2015.



Figure 6-12. Aerial photograph of the braided reach of the Animas River below Baker's Bridge area at river kilometer 64. (A) June 2014 (B) August 2015 immediately post Gold King passage, and (C) October 2015 where deposition would have been high upon exiting the canyon.

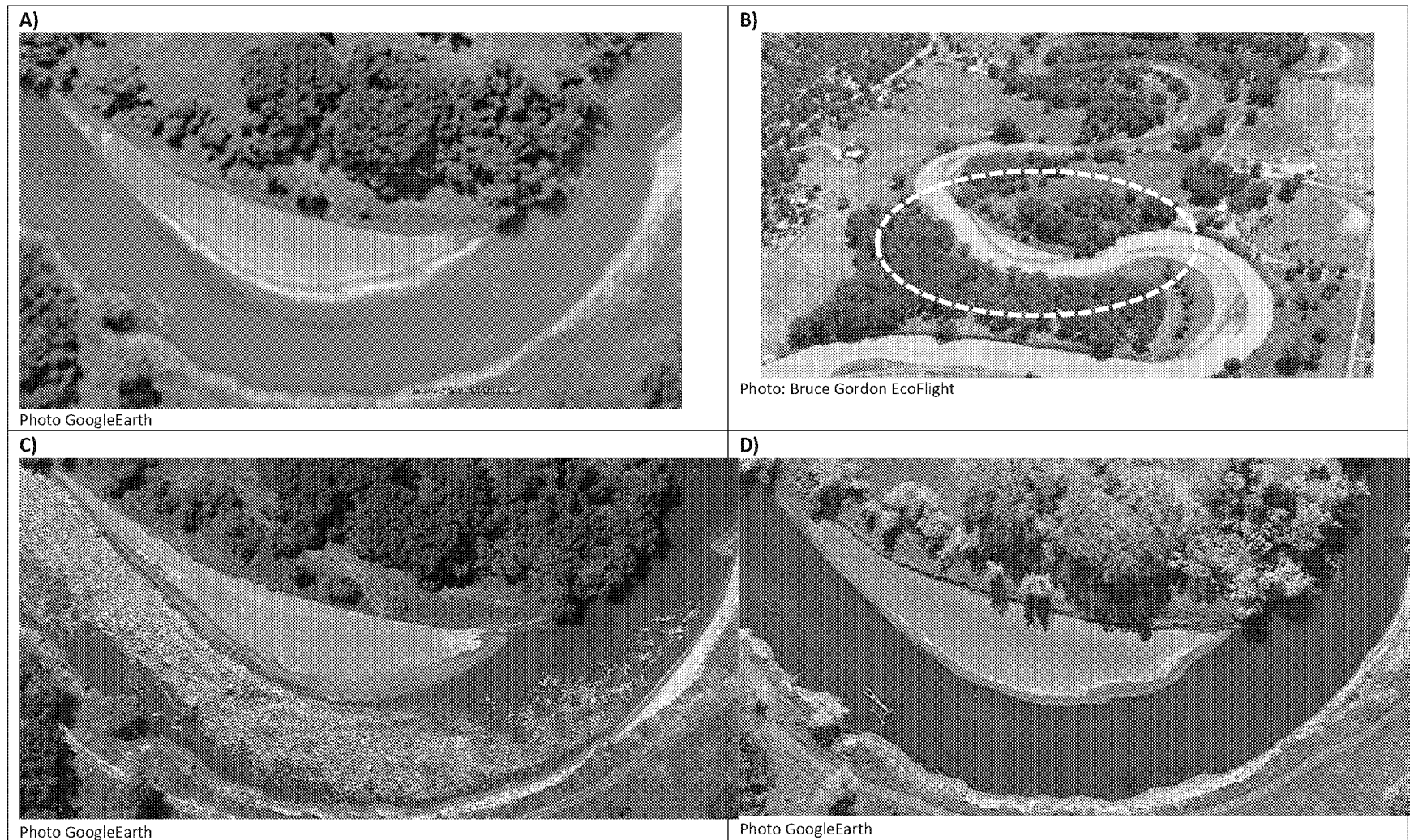


Figure 6-13. Meandering channel north of Durango. The meander pictured in (A) was photographed from the air as the Gold King plume passed (B). The same sediment bar is shown in 2014 from Google Earth imagery (C) and in October 2015 in (D). Gold King deposits were observed on the banks and bar in this reach.

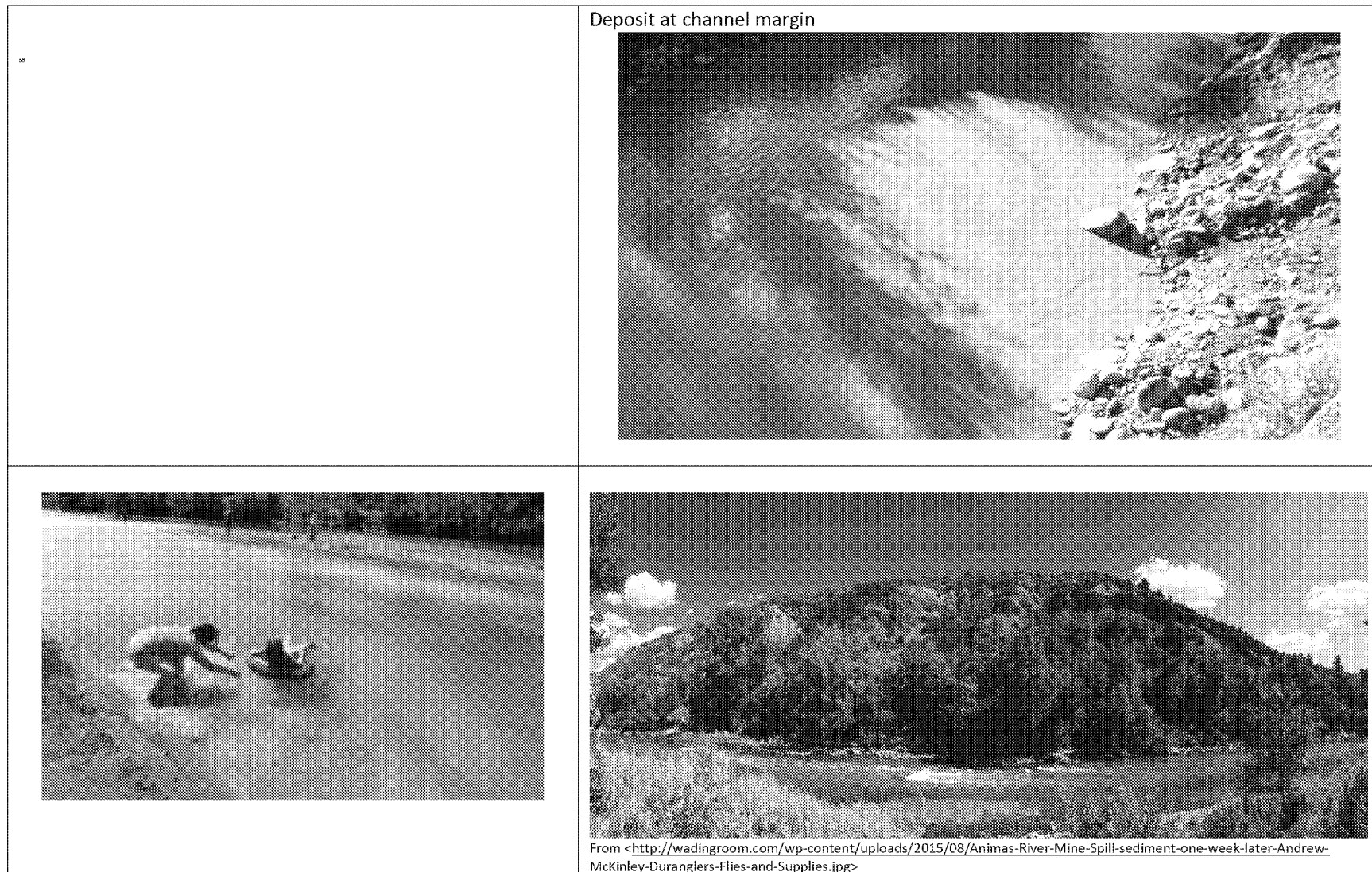


Figure 6-14. Channel margin deposits. Examples of channel deposits along the channel margin, event in swift flowing water in the mid Animas, closeup of plume water within 5 to 10 feet from the bank (B) and along the channel for recreationalist.

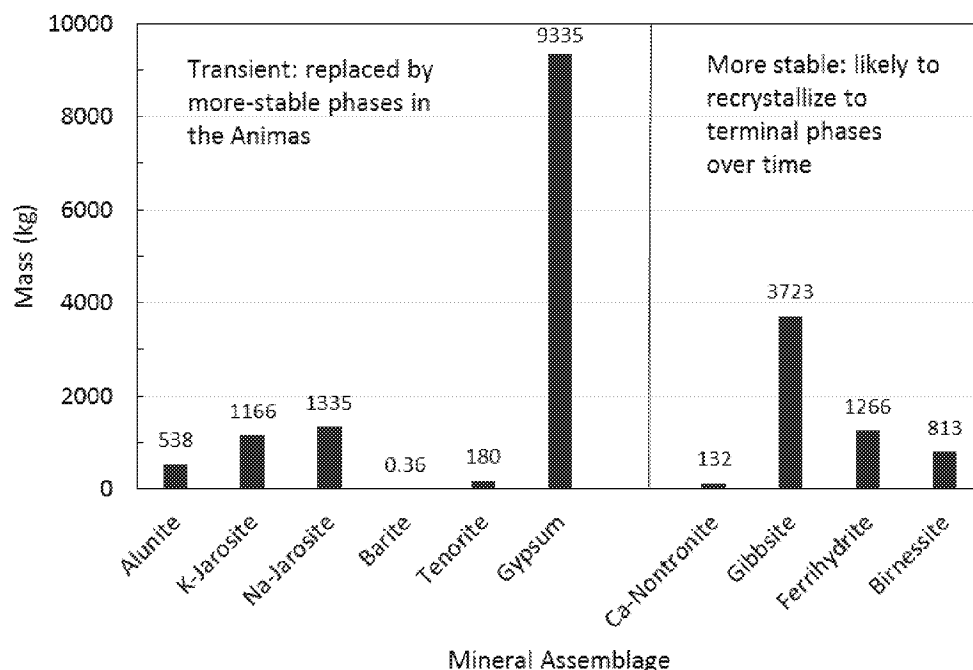


Figure 6-15. Masses of minerals precipitated from the release waters and Cement Creek water flowing with release waters) as these waters intermingled and reacted with Animas River water as estimated from thermodynamic modeling of titration of “Plume + Background Mean” water with calcite alkalinity that is present in the Animas (Figure 5-10). Cations initially in alunite and jarosite likely will ultimately enter the more stable gibbsite and ferrihydrite phases, respectively. Whether low trace levels of Ba and Cu will form discrete mineral phases such as barite and tenorite, respectively, or sorb to and isomorphically substitute directly in more stable mineral phases is uncertain, but ultimately these ions likely will be bound to more stable minerals and their aqueous concentrations maintained at low levels as suggested by modeling described later in this report. Nontronite is a commonly occurring smectite clay mineral. Gibbsite, ferrihydrite and birnessite are commonly occurring oxyhydroxide minerals and likely will recrystallize to similar, but still more stable, phases over time. See Appendix C for more discussion.

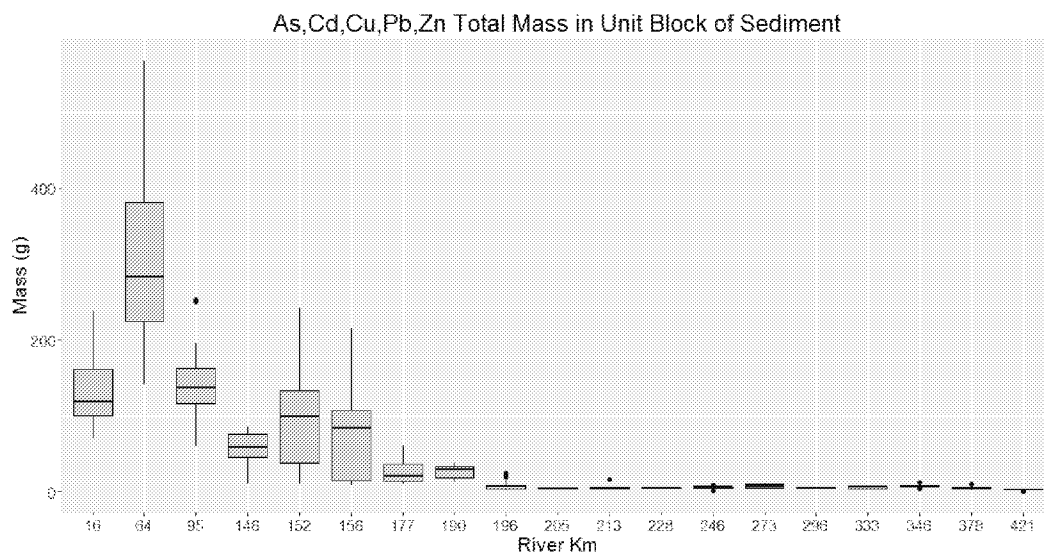


Figure 6-16. Statistical summary of summed metals mass per unit block of sediment 1 square meter x 5 cm depth collected during the and the months following the Gold King release. Metals include arsenic, cadmium, copper, lead, and zinc. The statistical distribution of cell bed sediment data collected in the Animas and San Juan Rivers are summarized as a box plot with mean 95% of observations and range. Data show the range of metals observed along the river length. The confluence of the Animas and San Juan Rivers occurs at 193 km.

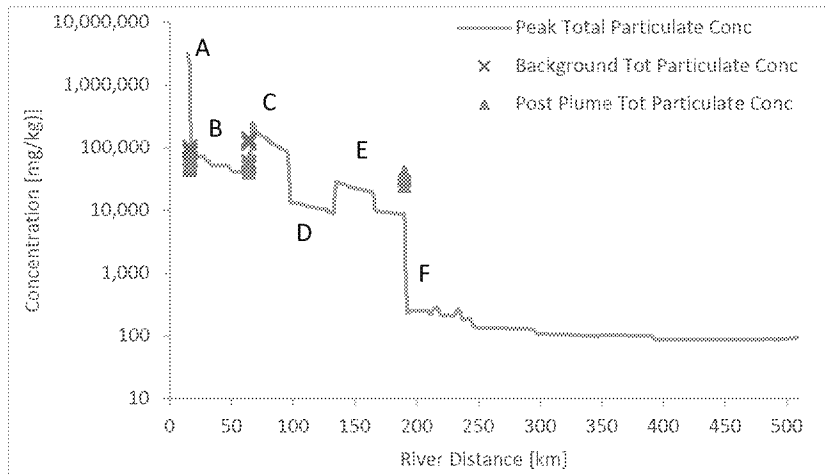


Figure 6-17. Simulated Peak Total Sediment Concentrations Along River. Simulated concentrations (orange line) of total particulate metals versus river distance plotted on a log-scale. Observed concentrations at three locations presented for background (before plume, blue X) and after plume (green triangle). Metal concentrations decline by orders of magnitude from the upstream to the downstream. Concentrations are highest with a large settling of metals upon entering the Animas River at Silverton (A). The concentrations in the sediments are less as the plume accelerates through the canyon reach within the San Juan National Forest between Silverton and Bakers Bridge (B) with little deposition. Bed sediment concentrations increase as the velocity of the river slows and mass deposits upon exiting the canyon north of Durango near Baker' Bridge (C). Deposition continued in the meandering reach through Durango. Bed sediment concentrations decrease past Durango (D) as the river accelerates through the straighter reaches characteristic of the lower Animas River. Deposition increases near the wider valley near Aztec NM (E) before reaching the end of the Animas at Farmington. When the plume reaches the San Juan (F), there is little deposition into the sediments as the plume seems to effectively flow through the San Juan River as if in a pipe with little settling relative to that observed in the Animas.

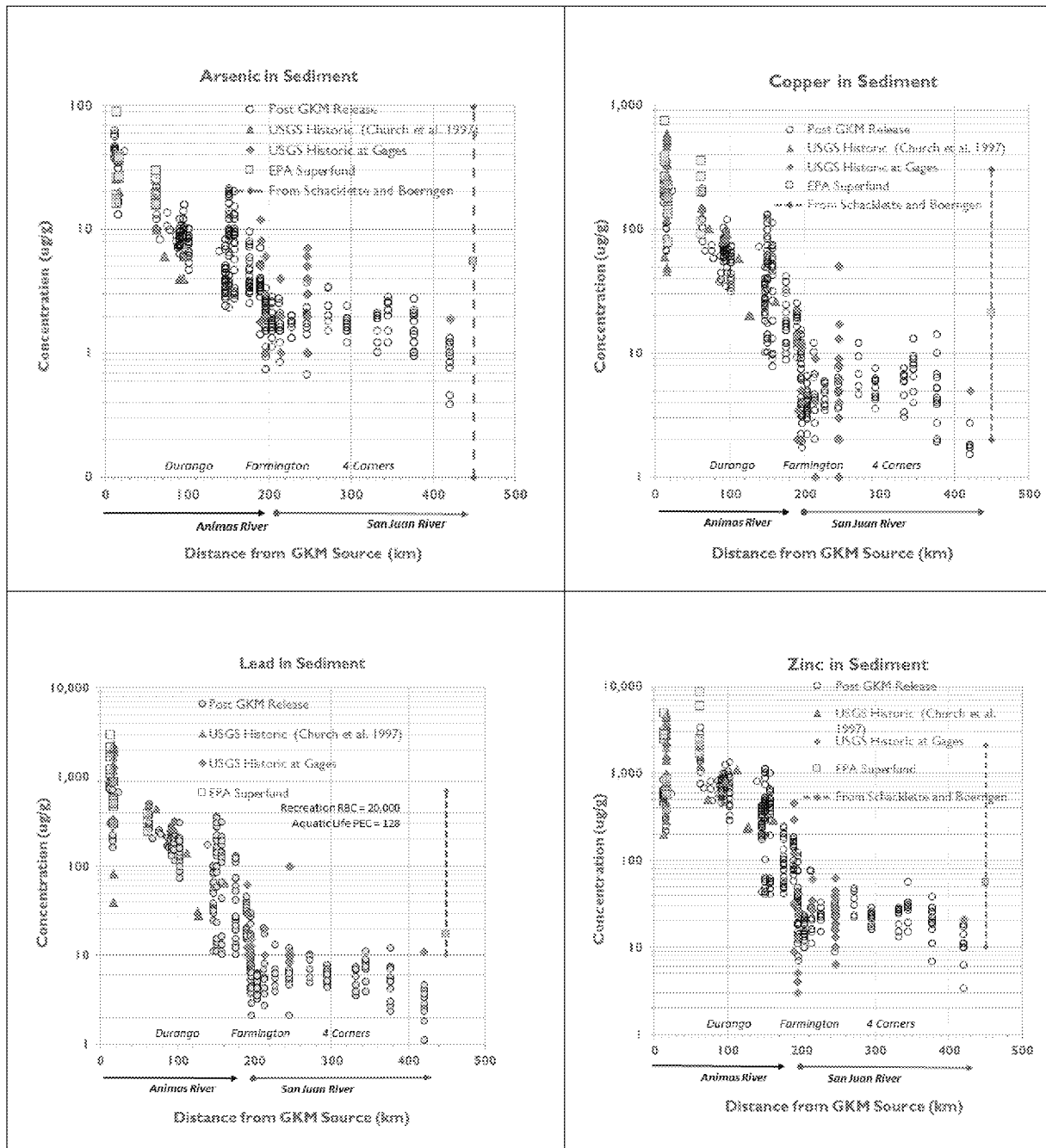


Figure 6-18. Bed sediment concentrations in the Animas and San Juan Rivers. Data include historical and Gold King Mine related sampling throughout the river system following the release. The USGS also occasionally collected metals data at gage locations. Also included are data collected by Church et al. as part of the Animas River synoptic survey of metals in sediments. Samples were collected and processed with a variety of objectives and techniques and there is undoubtedly some variability due to methods. However, concentrations collected after the release follow the same general data with a strong pattern of contamination in the headwaters declining to historic present in much of the Animas. Post Gold King release contamination is within the same range as pre-event for most places

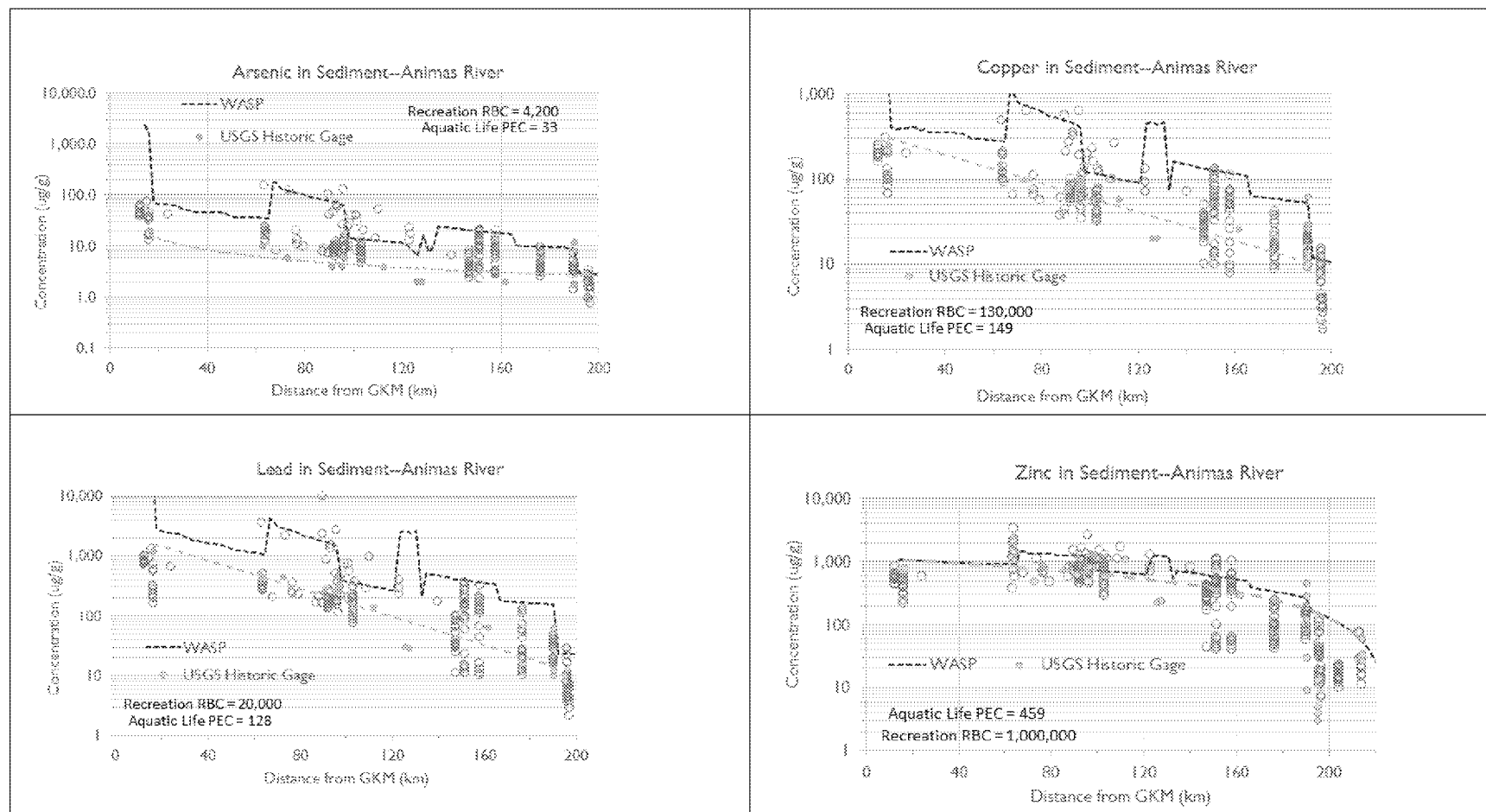


Figure 6-19. Simulated concentrations (orange line) of total particulate metals versus river distance plotted on a log-scale. Observed concentrations at three locations presented for background (before plume, blue X) and after plume (green triangle). Metal concentrations drop orders of magnitude from the upstream to the downstream. Concentrations are highest with a large settling of metals upon entering the Animas River at RK 12. The concentrations in the sediments drop as the plume speeds through the canyon (RK 20 to 50). The concentrations increase as the velocity of the river slows near Durango (RK 90). The concentrations in the sediment decrease for a distance past Durango, and then increase again near RK 130. When the plume reaches the San Juan at RK 195, there is very low deposition as the plume seems to effectively flow through the San Juan River as if in a pipe with little settling.

Table 6-1. Estimate of metals mass in three segments of the upper Animas River. Segment length and width was estimated from Google Earth imagery and software tools. Sediment concentrations were based on EPA remediation sampling (pre-event, 2010-2012). Plume deposits were determined from the empirical model mass estimates.

River Segment	Segment Length (m)	Segment Width (m)	Segment Area (m ²)	Sediment Bulk Density (kg/cm ³)	Segment 5-cm Depth Sediment Weight (kg)	Pre-Event Metal Conc (g/kg)	5-cm Depth Sediment Metal Weight (kg)	Estimated Plume-Deposited Metal (kg)	Plume Metal Deposits as % of Total
Cement to Silverton	3,900	10	39,000	0.0015	2,925,000	80	234,000	127,000	54.3%
Silverton to Bakers Bridge	50,000	20	1,000,000	0.0015	75,000,000	80	6,000,000	180,000	3.0%
Bakers Bridge to Durango	30,000	50	1,500,000	0.0015	112,500,000	40	4,500,000	92,000	2.0%

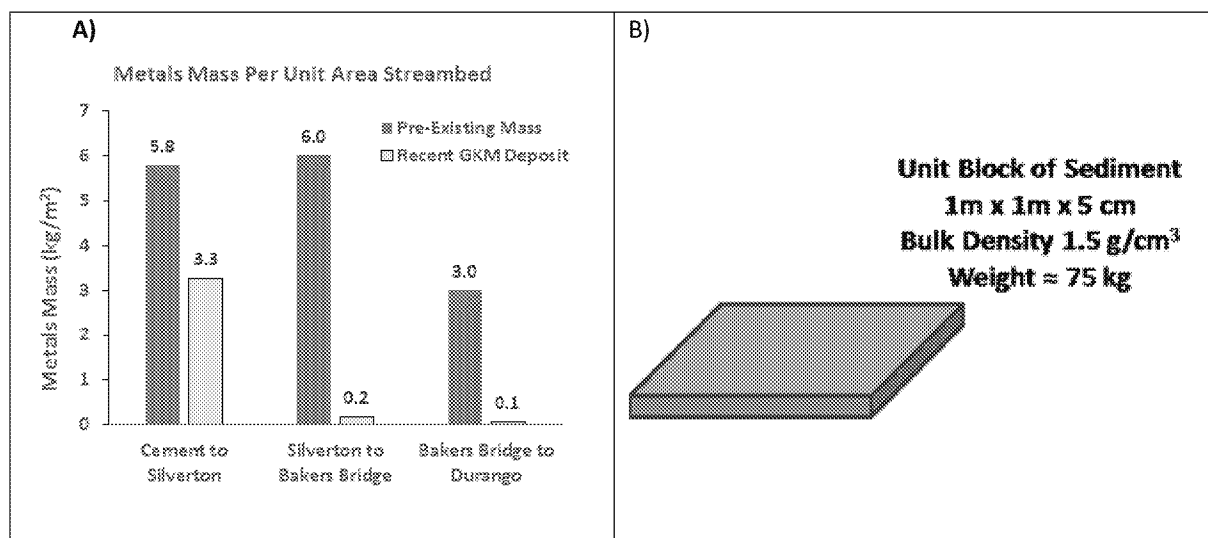


Figure 6-20. Comparison of recent GKM deposit to pre-existing mass. Metals mass in streambed sediments at three locations in the upper Animas expressed as mass per unit area of streambed, based on channel dimensions and sediment characteristics provided in Table 6-3 (A). Conceptual diagram of unit block of bed sediment (B). Metals deposition added a significant volume relative to pre-existing mass in the 2.4 km reach between Cement Creek and the site A72 near the USGS gage. Gold King plume deposits added relatively small amounts of additional mass in the reaches to existing metals contamination to sediments between A72 below Silverton and Durango.

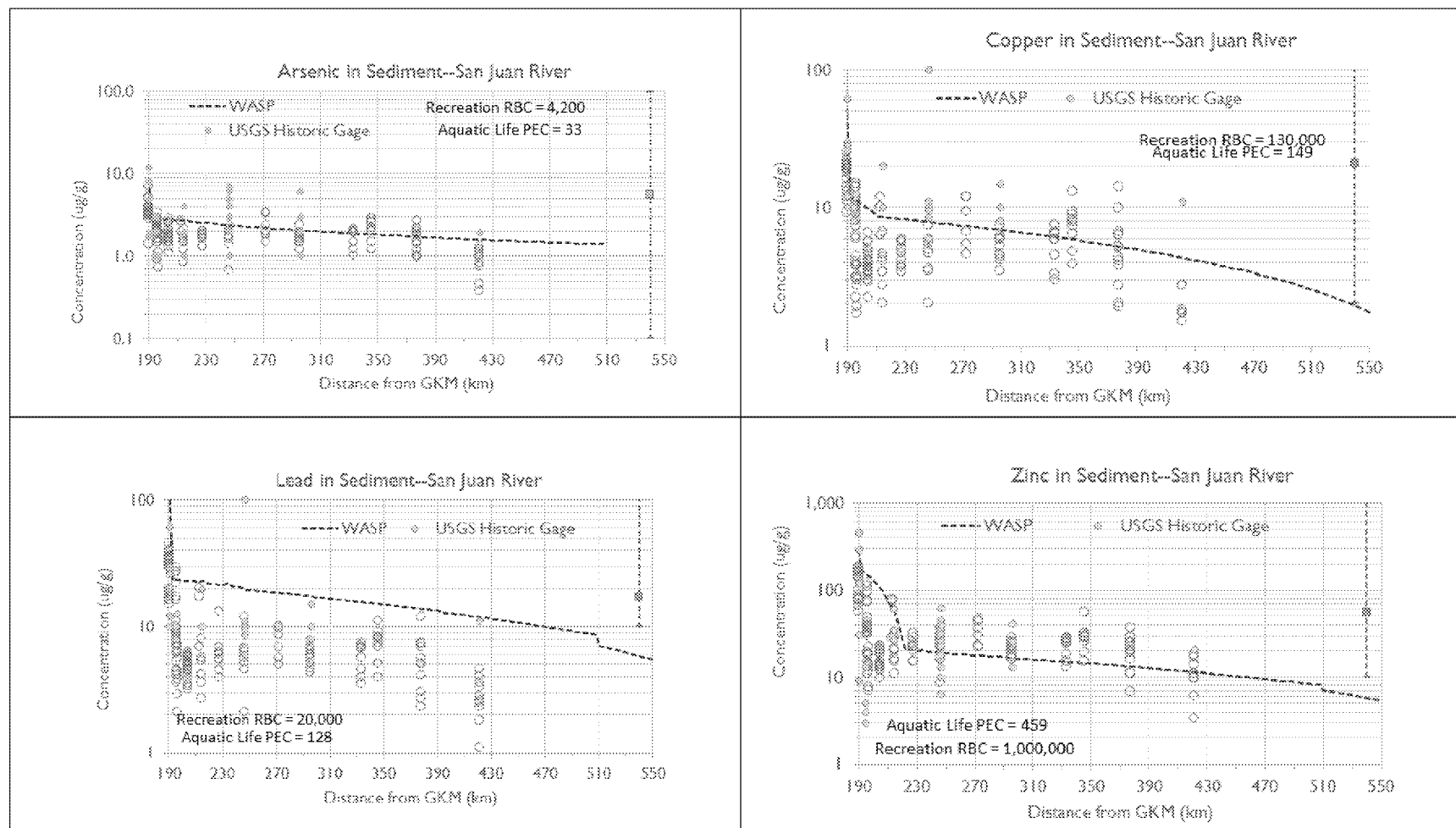


Figure 6-21. San Juan bed sediments. Concentration of four metals in the streambed of the San Juan River from its junction with the Animas at Farmington to Lake Powell. Samples were collected as Gold King release monitoring (gray circles). There was some data collected periodically by USGS at gages (yellow circles). Plotted on each graph is the range of metal concentrations in soils and surficial deposits in the western United States reported by Shacklette *et al.* (1982) as reference for the natural range of metals in sediments. San Juan bed sediments tend to be on the low end of this range.

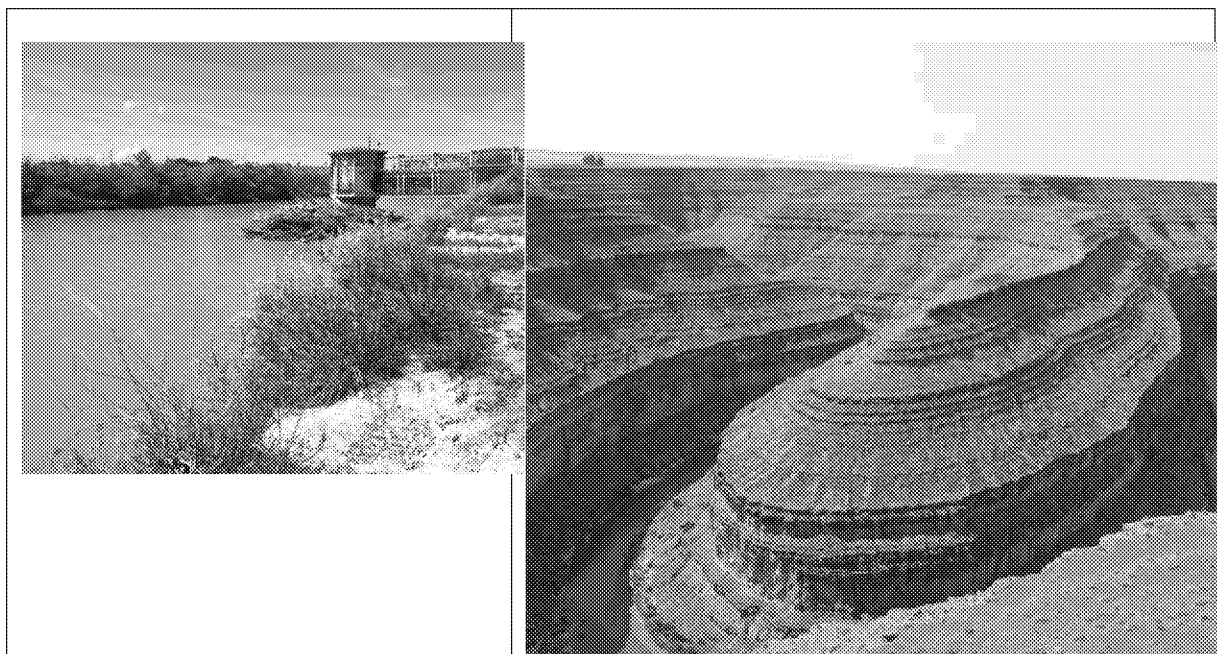


Figure 6-22 Photographs at of the San Juan River at Ship Rock (left) and as the river heads into Lake Powell west of Mexican Hat, UT (right).

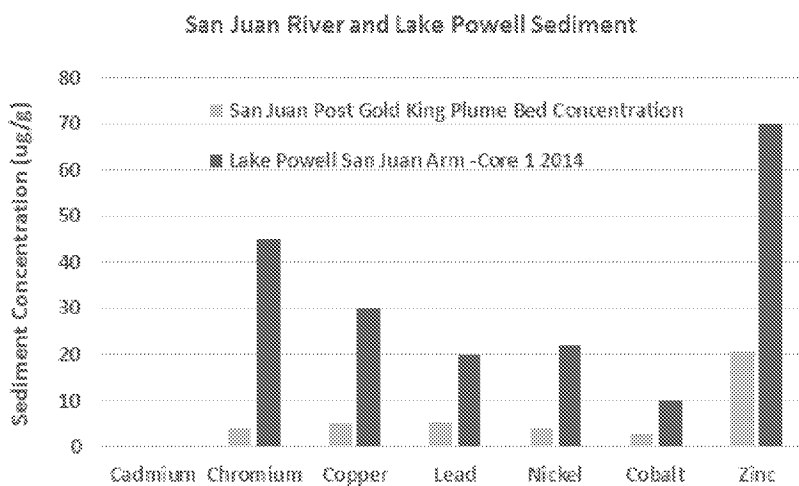
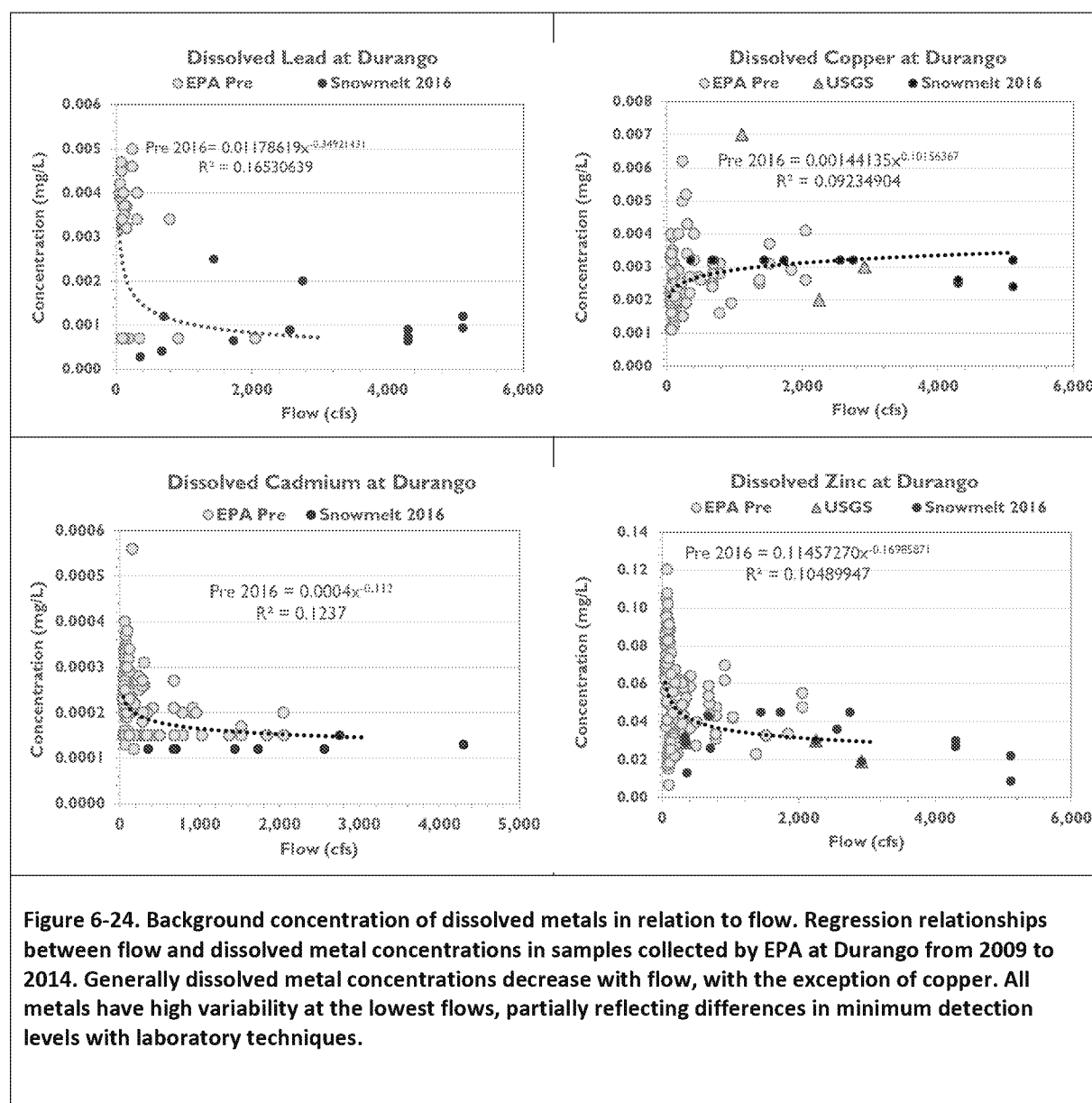
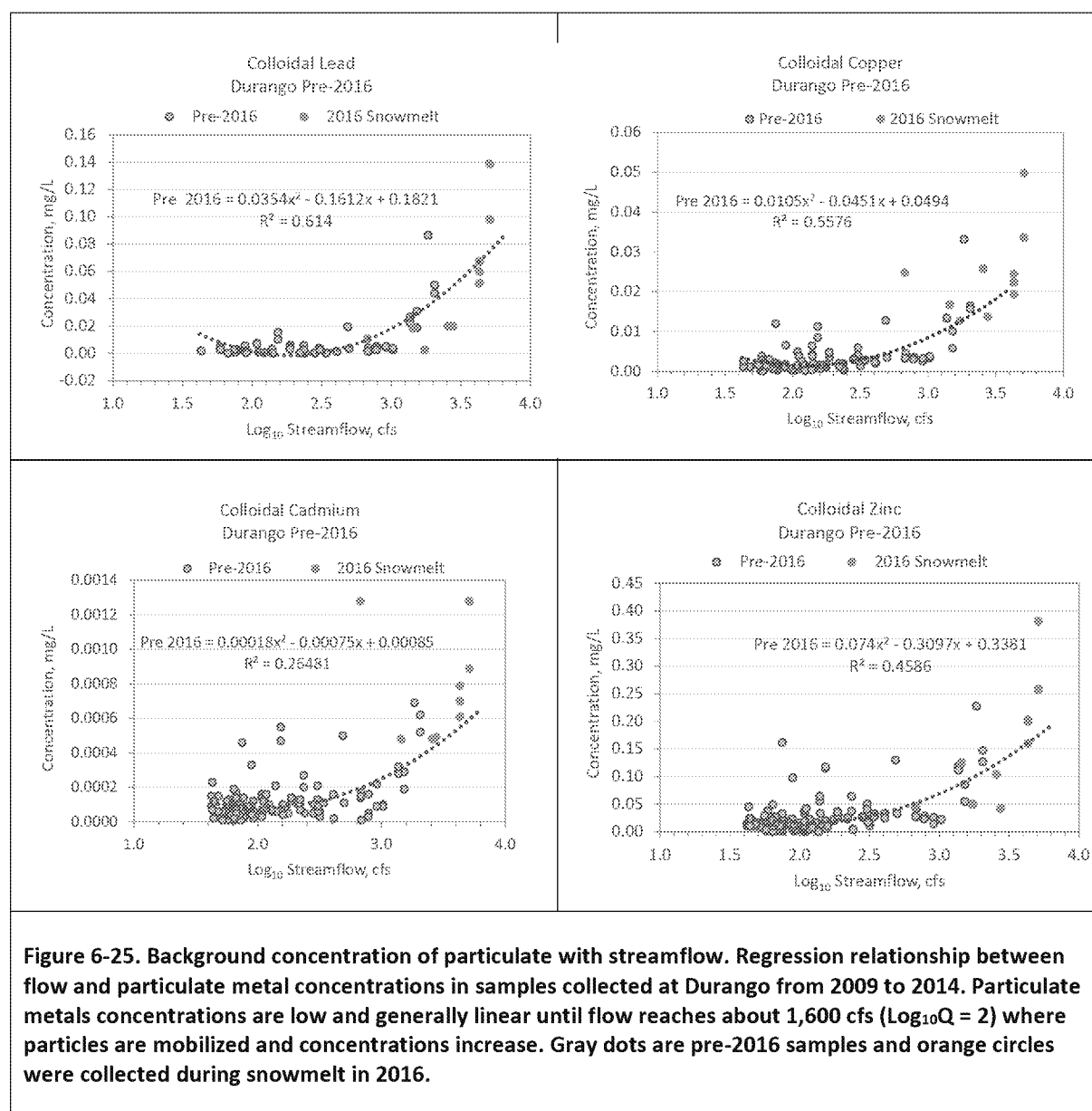


Figure 6-23. Comparison of metals concentrations in the streambed of the San Juan River at Mexican Hat about 50 km from Lake Powell and metal concentration in the top layers of lake core samples reported in 2014 [need ref]. Metals are more concentrated in the lake cores than observed in the river bed.





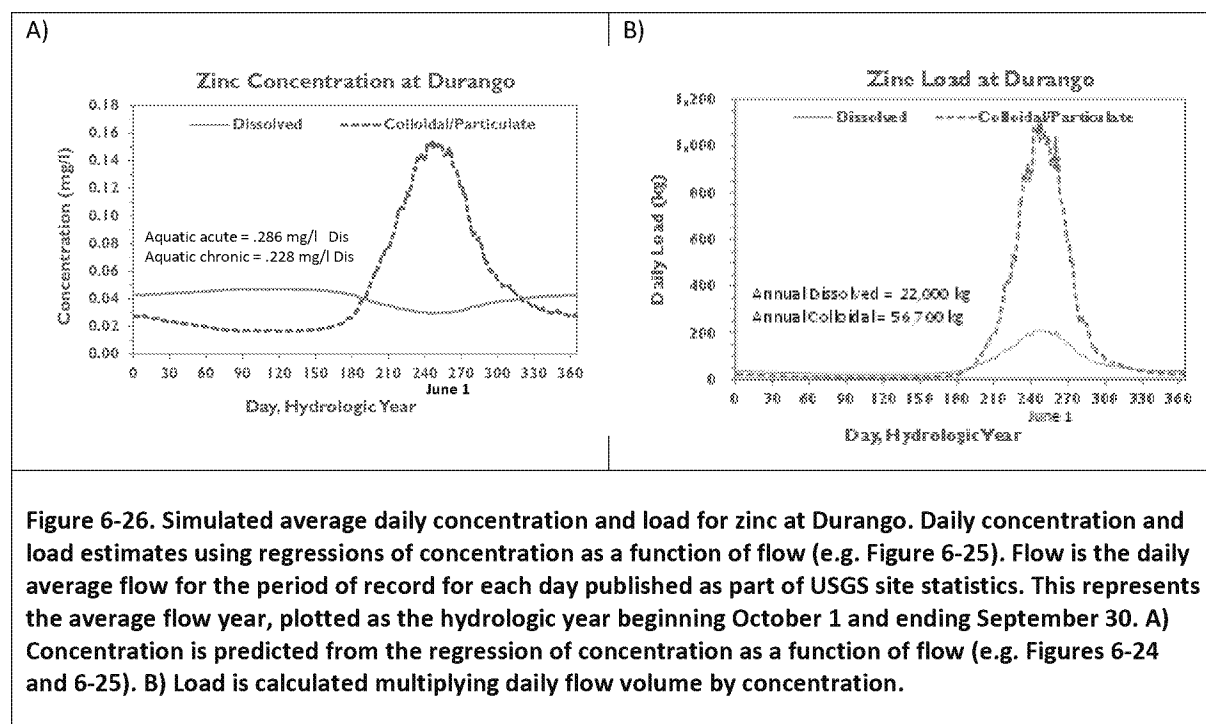


Table 6-2. Average annual metals dissolved and particulate load of the Animas River at Durango. Daily load as shown in Figure 6-26 is summed for the year. The mass of metals transported in the Gold King plume at Durango (river kilometer 94.5). The plume generally transported a volume of about 1-2% of the annual load.

Average Annual Load at Durango Pre-2016				Gold King Plume Load at Durango			
	Dissolved (kg)	Particulate (kg)	Total (kg)		Dissolved (kg)	Particulate (kg)	Total (kg)
Metal				Metal			
Aluminum	24,030	771,822	795,852	Aluminum	84	10,310	10,394
Iron	29,729	1,309,661	1,339,390	Iron	154	61,484	61,638
Manganese	28,981	132,088	161,069	Manganese	731	125	856
Lead	682	13,808	19,947	Lead	1	1,049	1,050
Copper	1,819	7,067	8,886	Copper	8	199	207
Zinc	22,375	59,191	81,566	Zinc	105	521	626
Cadmium	116	168	284	Cadmium	1	2	2

Table 6-3. Comparison of Gold King plume transport at Durango compared to the mass carried during the peak days of snowmelt runoff. The Gold King plume mass was similar to one to two days of mass transported during high snowmelt. Notably high during the Gold King plume was colloidal/particulate iron and lead and dissolved manganese.

Metal	Colloidal		Dissolved	
	Gold King Plume (kg)	Peak Day Snowmelt (kg)	Gold King Plume (kg)	Peak Day Snowmelt (kg)
Aluminum	10,300	14,000	84	320
Iron	61,500	23,000	154	460
Manganese	125	2,500	731	200
Lead	1,050	425	1	5
Copper	200	150	8	20
Zinc	520	1,100	105	250
Cadmium	2	3	1	1

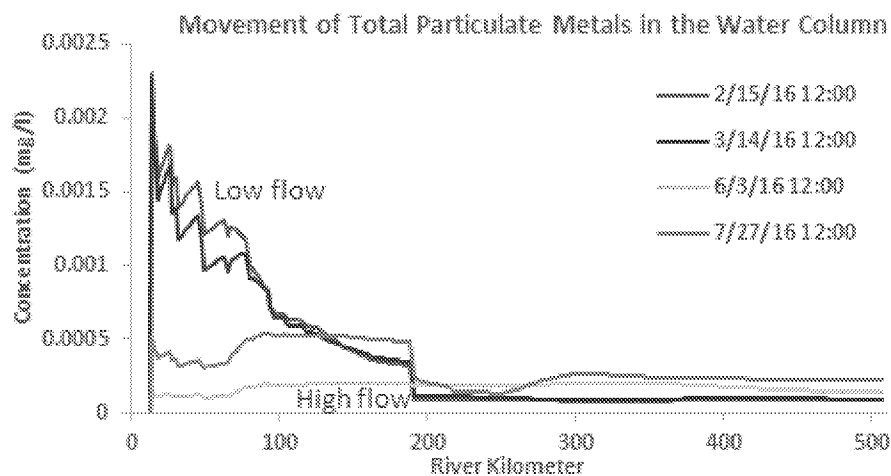


Figure 6-27. GKM WASP estimated summed total concentrations during spring snowmelt. To approximate a worst-case scenario, 3 cases were modelled where all metals in the sediments were instantaneously mixed with the overlying water column and calculated the concentration for 4 flows, ranging from low to high flows. The simulation assumed all mass previously deposited after the Gold King plume was resuspended at the modeled flow. The highest concentration was right at Silverton, where the most metal was deposited. All concentrations < 1 mg

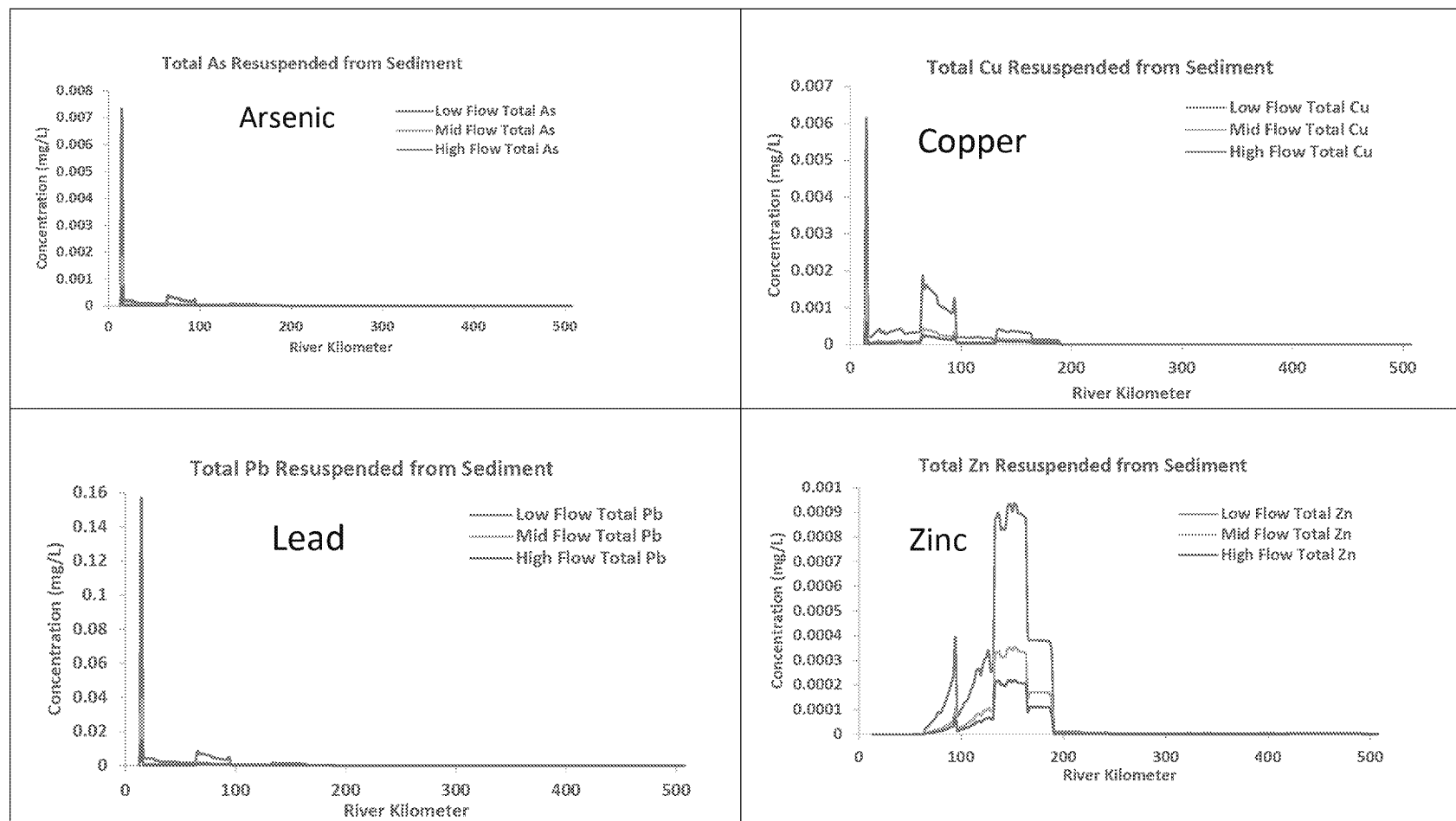


Figure 6-28. GKM WASP estimated concentrations during spring snowmelt. To approximate a worst-case scenario, 3 cases were modeled where all metals in the sediments were instantaneously mixed with the overlying water column and calculated the concentration for 3 flows. The simulation assumed all mass previously deposited after the Gold King plume was resuspended at the modeled flow. The highest concentration was right at Silverton, where the most metal was deposited. All concentrations < 1 mg/L. Results for individual metals are shown.

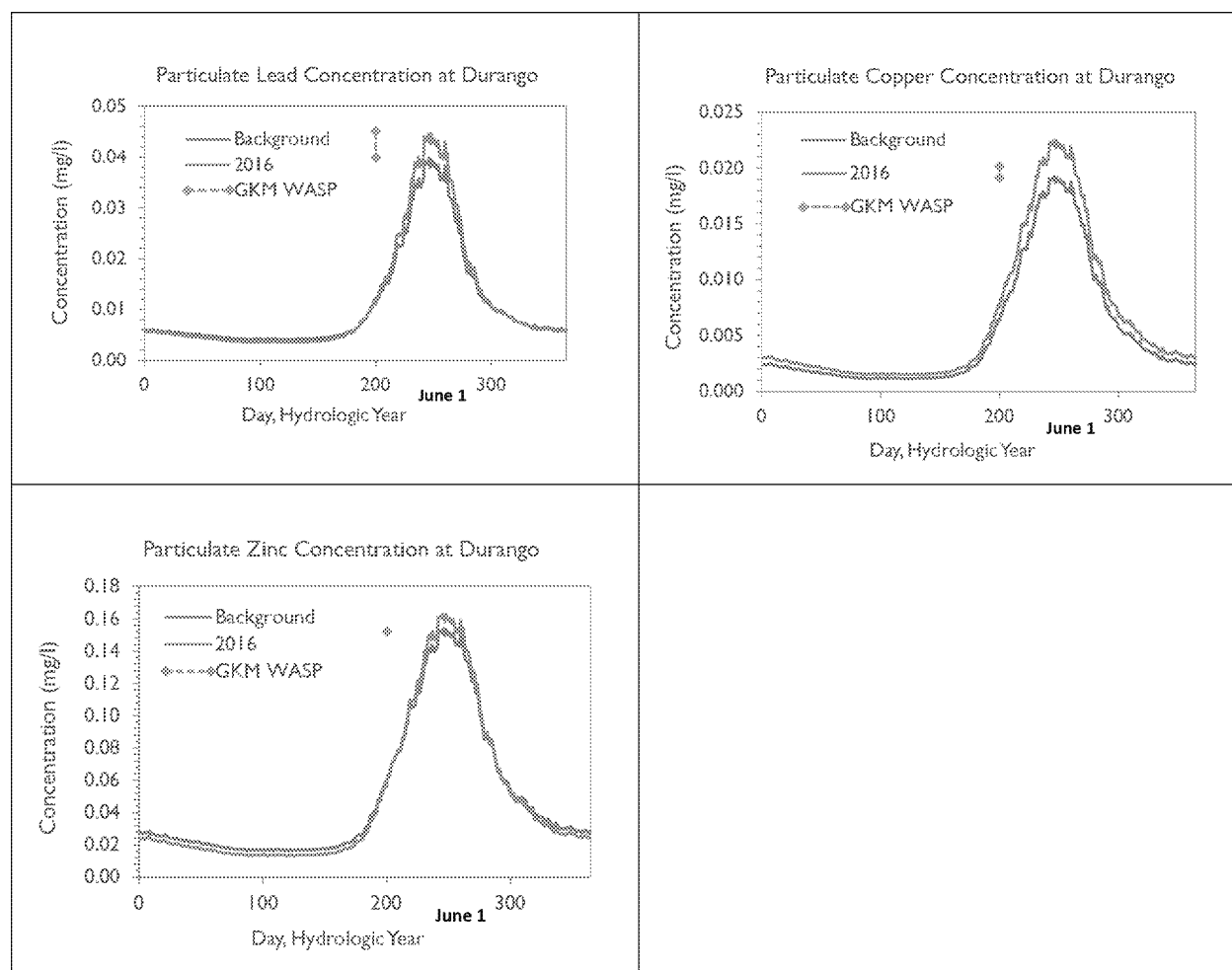


Figure 6-29. Empirical simulation of average daily metal load based on regressions using only historic data and average daily flow(background) and the updated regression with 2016 data and average daily flow (2016). The 2016 data increased the peak concentration a small amount at the maximum flows. The increase was in the same range as that predicted by GKM WASP (see Figure 6-28). The range of increase predicted by GKM WASP at higher flows is shown on these figures.

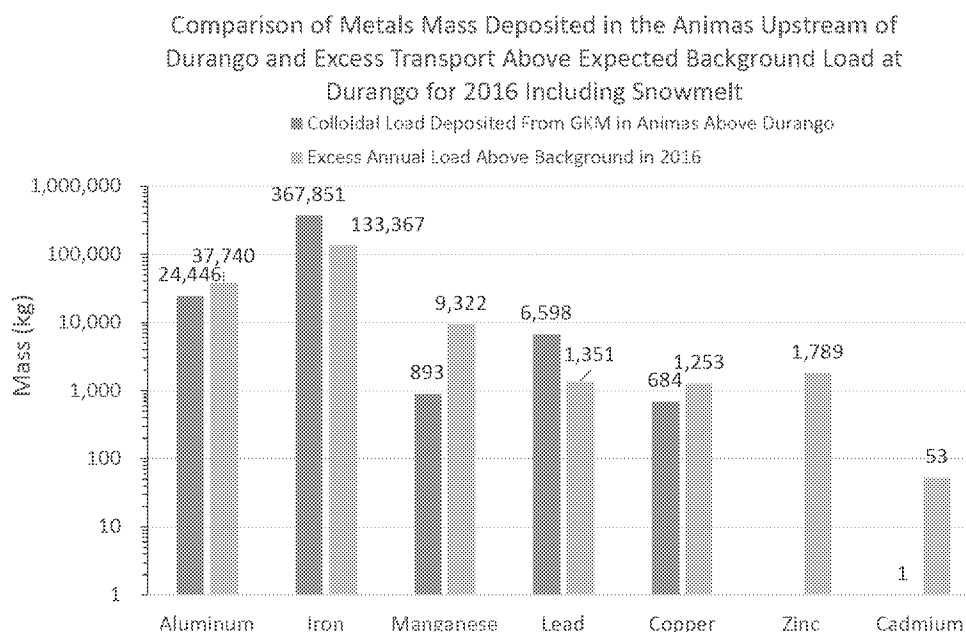


Figure 6-30. Gold King load relative to excess in 2016. Comparison of 2016 annual metals load in excess of average annual load compared to the mass of metals deposited from Silverton to Durango from the Gold King plume. Background mass is computed from pre-event regressions of concentration as a function of flow and 2016 adds 2016 snowmelt data to adjust the regression. Both background and 2016 are computed with average daily flow at the USGS gage computed for the duration of the record. Excess load in 2016 is the background average load subtracted from 2016. Excess load in 2016 is similar to the mass of each metal deposited during the plume.